Wave Function Engineering for Normal Incidence Infrared Detection

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Abstract

The quantum well infrared photodetector (QWIP) is an artificially engineered semiconductor multilayer structure designed to absorb (and detect) infrared radiation. The major drawback to QWIPs is that they have relatively low absorption quantum efficiencies because quantum mechanical selection rules prevent the absorption of normal incidence radiation in QWIPs. To circumvent this problem, researchers have designed various backside gratings for reflecting normal incidence radiation back through the QWIP structures at an angle. To date, the light-coupling efficiencies of these grating structures are still insufficient for achieving high absorption efficiency, particularly in the case of multicolor and broad-band QWIPs where the grating designs must be capable of coupling multiple wavelengths. We propose the island insertion infrared detector (I^3D) as an alternative solution to the normal incidence problem. At a fundamental level, the normal incidence problem arises mainly as a consequence of the fact that the wave functions of the quantum mechanical states involved in the relevant optical transitions do not contain enough variations in the lateral directions (directions parallel to the QWIP structure interfaces). Our device design introduces perturbations inside the quantum wells to break the translational symmetries in the directions parallel to the interfaces. Specifically, we place a sub-monolayer of InAs in the middle of each of the GaAs quantum wells. The lattice mismatch between the two materials causes InAs to form patches or islands of low-potential regions. Simulations have shown that, provided that the island sizes are sufficiently large (on the order of the GaAs quantum well width), the wave functions will be localized by the islands to provide the lateral variations needed for absorbing normal incidence radiation. One advantage of the I^3D design is that it is sufficiently similarities to QWIPs such that the fabrication procedures and device optimizing concepts may be borrowed in a straight-forward manner. It also differs substantially from QWIPs: transitions in the I^3D involve localized quantum dot-like states, while those in the QWIP involve only laterally translational invariant 2D quantum well states. It is this fundamental difference that allows this device to absorb normal incidence radiation for achieving higher quantum efficiency

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David Ting

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Collaborators

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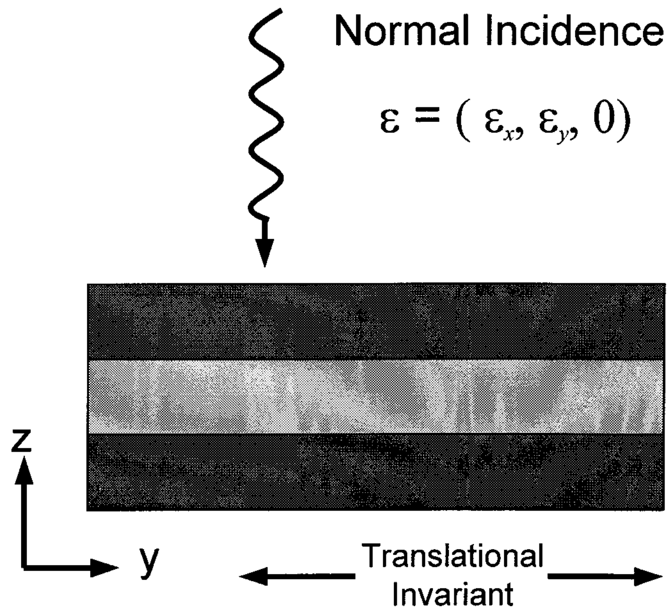
Outline

- Introduction: The normal incidence problem in intersubband quantum well detectors
- Proposed Wave Function Engineering Solution: Island Insertion Infrared Detector (I^3D)
- Results and Conclusions

The Normal Incidence Problem

- Oscillator Strength: $f_{12} \propto |\langle\psi_1|\varepsilon\cdot\mathbf{p}|\psi_2\rangle|^2 \propto |\langle\psi_1|\ \varepsilon_x(\partial/\partial x) + \varepsilon_y(\partial/\partial y) + \varepsilon_z(\partial/\partial z)\ |\psi_2\rangle|^2$
- Envelope Functions have no variations in lateral (x,y) directions.
- Normal Incidence: $\varepsilon = (\ \varepsilon_x, \varepsilon_y, 0)$

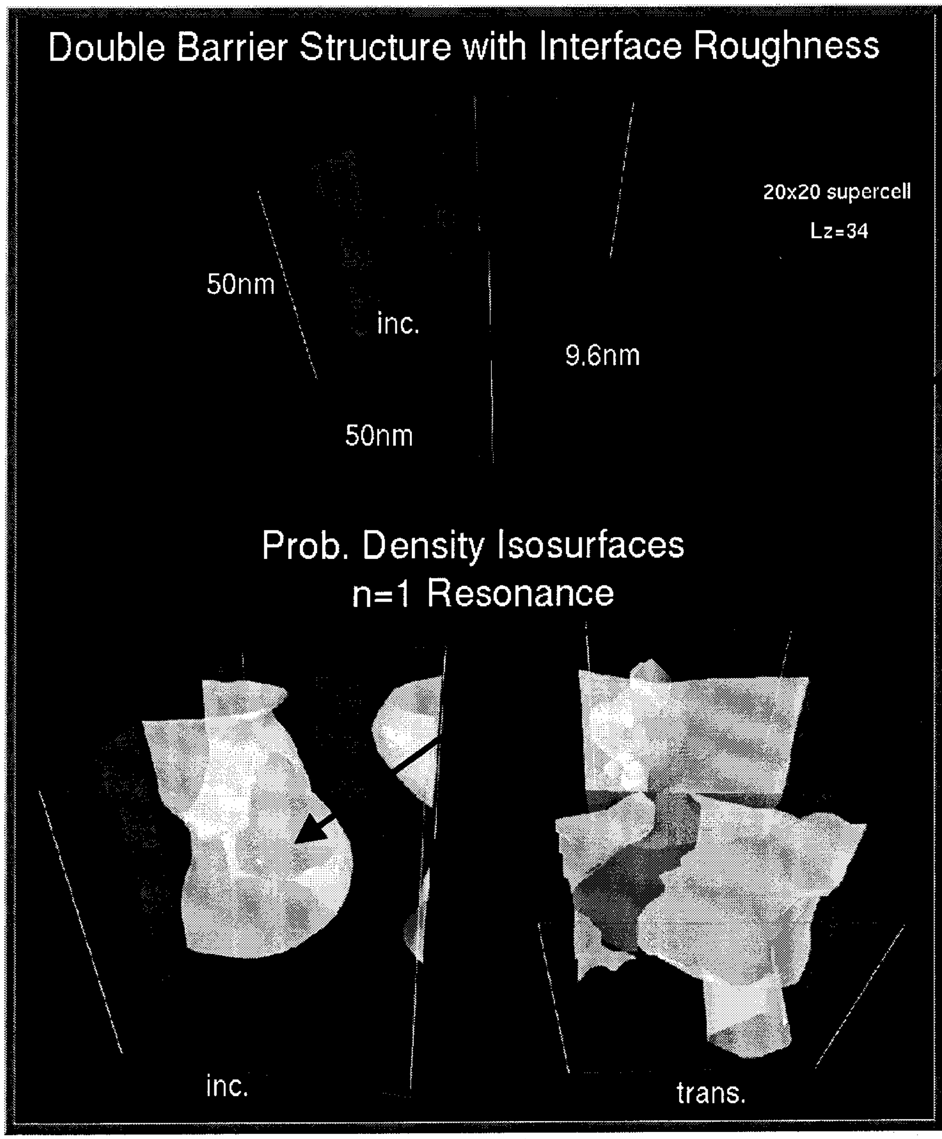
No oscillator strength for normal incidence radiation !



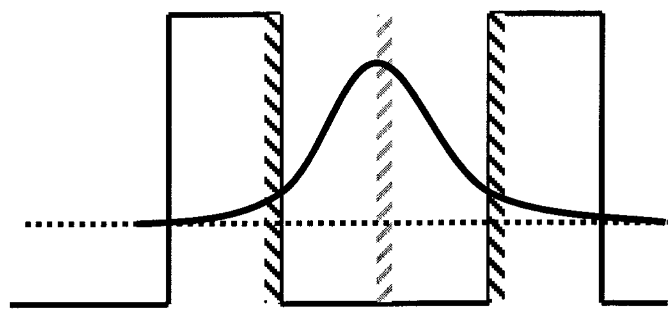
Solutions to the Normal Incidence Problem

- Oscillator Strength: $f_{12} \propto |\langle\psi_1|\varepsilon\cdot\mathbf{p}|\psi_2\rangle|^2$
- Current solution: Introduce grating structures to change direction of light.
- A Complementary solution: Introduce lateral variations in the envelope functions.

Perturbing Quantum Well Wave Functions: Lessons from Interface Roughness Studies

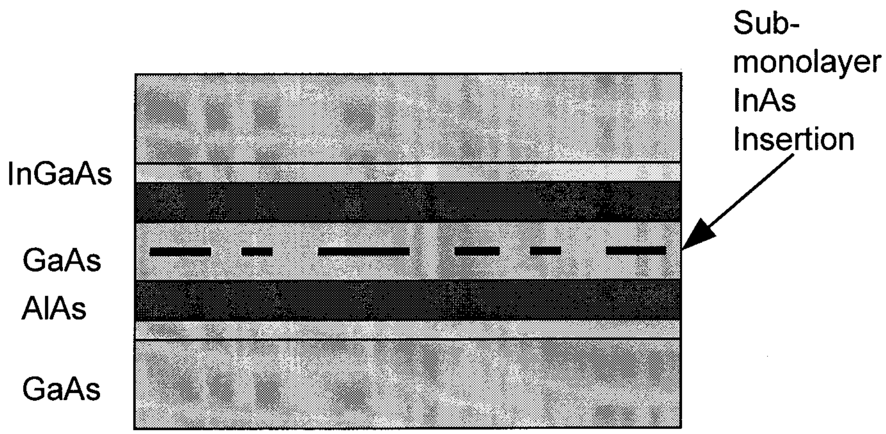


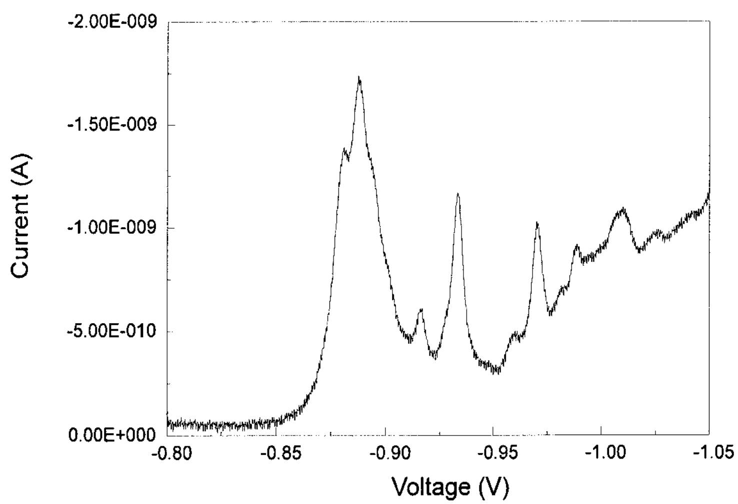
- Study of interface roughness effects in double barrier resonant tunneling diodes found interface roughness can induce localization of resonant state wave functions, provided island sizes are sufficiently large. [D. Z.-Y. Ting, S. K. Kirby and T. C. McGill, Appl. Phys. Lett. **64**, 2004 (1994)]



- Probability density is relatively small at the interfaces. Could enhance localization effects by introducing roughness in the middle of the quantum well where PD is highest.

Double Barrier Structures with Mid-Well Island Insertion



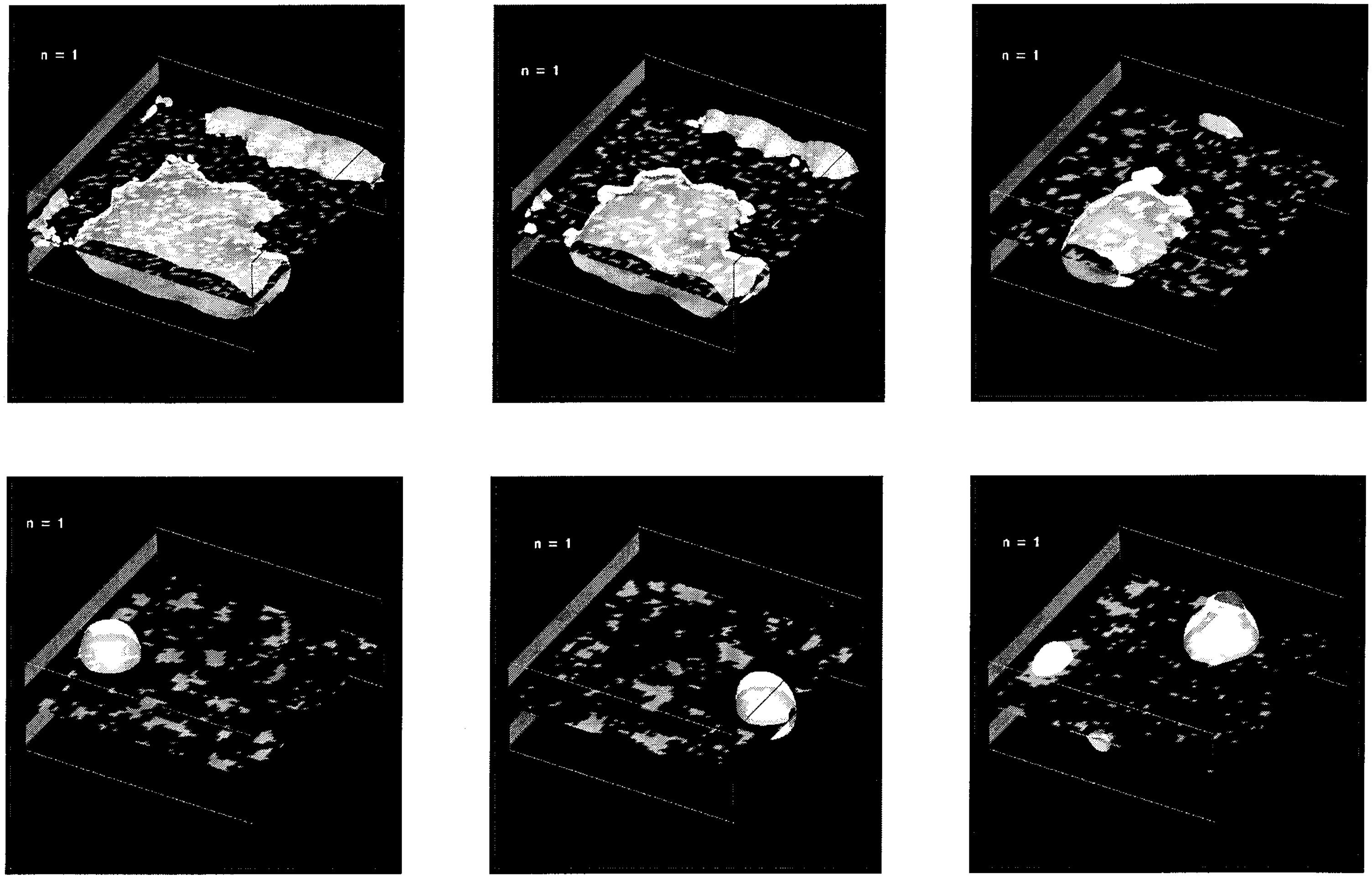


- GaAs/AlAs DBRTD with 1/8 monolayer InAs insertion and InGaAs emitter.
- Measurements showed series of resonance attributed to self-organized InAs island formation.
- In agreement with modeling results.

[J. N. Wang, R. G. Li, Y. Q. Wang, W. K. Ge, and D. Z.-Y. Ting, *Microelectronic Engineering*, **43** 341-347 (1998).]

Modeling Results: Lowest Island Insertion States in Various Island Configuration

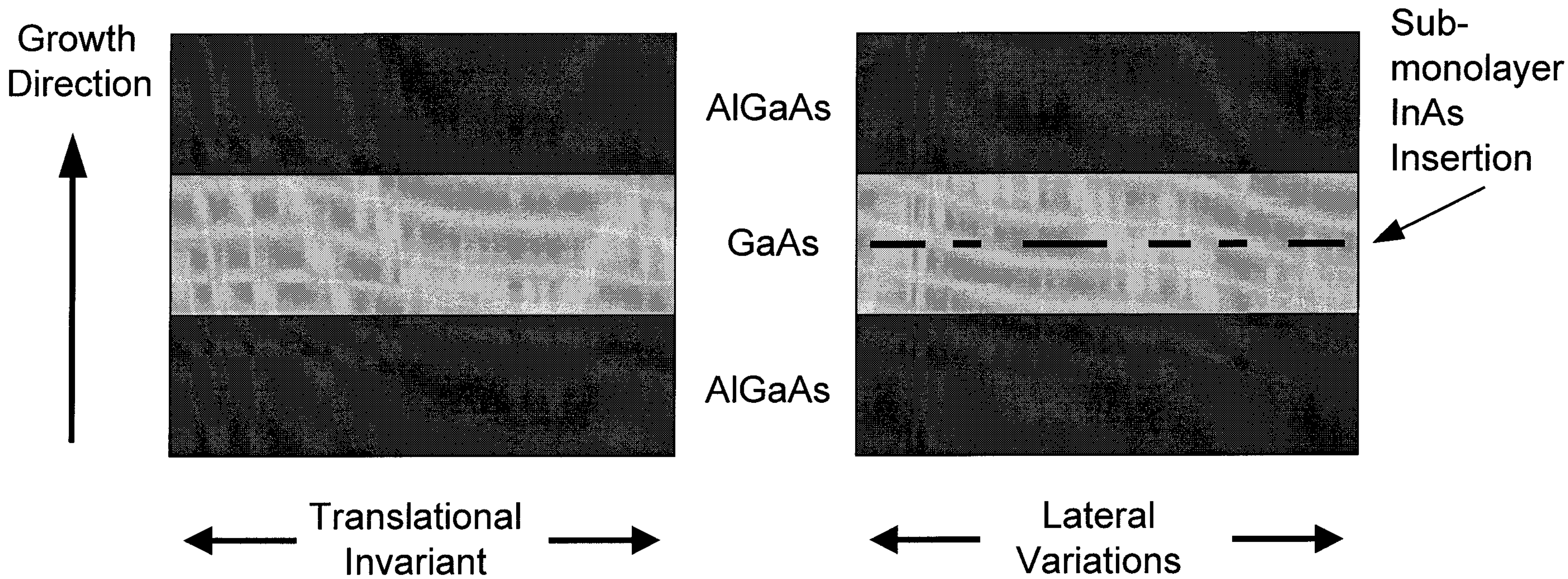
Average Island Size = 2.8, 2.3, 3.9, 6.4, 10.3, 15.7 nm



QWIP vs. I^3D

Quantum Well Infrared Photodetector

Island Insertion Infrared Detector



Island Insertion Infrared Detectors

- Similar to QWIPs in growth and processing.
- Wave functions of states involved in optical transition engineered to yield absorption of normal incidence radiation.
- Prototype device structure grown and being tested.
- Dependence on island size and placement to be investigated.